Characterization of the Physics of Electrons Confined to One Dimension

Carbon Nanotubes used to Study Magnetic Properties, Scattering, and Metallic Behavior

A research team led by Paul McEuen, in collaboration with Richard Smalley at Rice University, has combined experiment with theory to reveal, at a new level of detail, the behavior of electrons in a one-dimensional world. Reports of their work have appeared in *Nature* and *Physical Review Letters*.

Over 30 years ago, theorists began to predict that electrons would behave differently in one dimension (1-D) than in two or three dimensions because of the increased Coulomb interactions between them. This is analogous to the fact that two cars on a one-lane highway are much more likely to "interact" than two planes flying through space. The recent discovery of single-wall carbon nanotubes (SWNTs), which consist of two dimensional graphene sheets rolled into one-dimensional nanometer-diameter cylinders, offered an ideal opportunity to study this phenomenon. However, performing electronic experiments with SWNTs has been challenging, due, in part, to difficulties in handling such tiny objects. The LBNL team therefore developed new fabrication and handling techniques to construct and study the nanosized electronic devices made from the tubes (MSD Highlight 98-3). With these devices, and theoretical support, they performed a series of fundamental experiments involving the transport of electrons in this system.

In a first group of experiments the team studied electrical conduction in very short tubes. They found that successive electrons added to the tubes entered with alternating spins, resulting in an overall nonmagnetic state. Thus, each added electron effectively "senses" the presence of the other electrons in the tube through the Coulomb interaction and adjusts its spin accordingly.

A second group of experiments relied on previous LBNL work (MSD Highlight 96-7) which had shown that SWNTs are generally 1-D semiconductors if rolled in a spiral pattern and metals if rolled evenly. The team compared these two type of nanotubes by measuring the conduction through "ropes" made up of several concentric tubes. They had previously shown that, in nearly all cases, although conduction through the rope occurs via a single tube in the rope, the neighboring tubes represent sources of local disorder and influence that conduction. They then used an AFM tip to locate individual scattering sites (which degrade the conductance) in both semiconducting and metallic tubes (see figure). The team found that the perturbations strongly affected the conducting properties of semiconducting nanotubes but had little effect on metallic tubes. This result was shown theoretically to be related to the unusual nature of the band structure in carbon nanotubes and demonstrated that electrons in metallic tubes can travel without scattering ("ballistically") over micron length scales, even at room temperature.

Finally, the fact that the metallic nanotubes are nearly perfect conductors then made it possible for the researchers to test a long-standing prediction about the fundamental nature of electrons in one dimension. Due to the predominance of the Coulomb interaction, electrons in 1-D are predicted to behave like a "Luttinger liquid" in which the electrons move collectively rather than individually. As a result, the conductance goes to zero at low temperatures as a power law in the temperature. The team measured the conductance of single 1-D metallic nanotubes as a function of temperature and observed exactly this behavior, providing the most definitive demonstration of a Luttinger liquid to date and clearly showing the uniquely different nature of one-dimensional metals.

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